

**SERVO WRITING A DISK DRIVE BY SYNCHRONIZING A SERVO WRITE
CLOCK TO A HIGH FREQUENCY SIGNAL IN A SPIRAL TRACK**

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to disk drives for computer systems. More particularly, the present invention relates to servo writing a disk drive by synchronizing a servo write clock to a high frequency signal in a spiral track.

Description of the Prior Art

When manufacturing a disk drive, product servo sectors 2₀-2₇ are written to a disk which define a plurality of radially-spaced, concentric data tracks 6 as shown in the prior art disk format of FIG. 1. Each product servo sector (e.g., servo sector 2₄) comprises a preamble 8 for synchronizing gain control and timing recovery, a sync mark 10 for synchronizing to a data field 12 comprising coarse head positioning information such as a track number, and servo bursts 14 which provide fine head positioning information. During normal operation the servo bursts 14 are processed by the disk drive in order to maintain a head over a centerline of a target track while writing or reading data. In the past, external servo writers have been used to write the product servo sectors 2₀-2₇ to the disk surface during manufacturing. External servo writers employ extremely accurate head positioning mechanics, such as a laser interferometer, to ensure the product servo sectors 2₀-2₇ are written at the proper radial location from the outer diameter of the disk to the inner diameter of the disk. However, external servo writers are expensive and require a clean room environment so that a head positioning pin can be inserted into the head disk assembly (HDA) without contaminating the disk. Thus, external servo writers have become an expensive bottleneck in the disk drive manufacturing process.

The prior art has suggested various "self-servo" writing methods wherein the internal electronics of the disk drive are used to write the product servo sectors independent of an external servo writer. For example, U.S. Patent No. 5,668,679 teaches a disk drive which

1 performs a self-servo writing operation by writing a plurality of spiral tracks to the disk which
2 are then processed to write the product servo sectors along a circular path. Each spiral track is
3 written to the disk as a high frequency signal (with missing bits), wherein the position error
4 signal (PES) for tracking is generated relative to time shifts in the detected location of the spiral
5 tracks. In addition, the '679 patent generates a servo write clock by synchronizing a phase-
6 locked loop (PLL) to the missing bits in the spiral tracks. However, the limited frequency of the
7 missing bits as well as the limited resolution of the circuitry for timing the occurrence of the
8 missing bits may cause timing errors in the servo write clock.

9 There is, therefore, a need to better synchronize a servo write clock when servo writing a
10 disk drive by servoing on spiral tracks.

11 SUMMARY OF THE INVENTION

12 The present invention may be regarded as a method of writing product servo sectors to a
13 disk of a disk drive. The disk drive comprises control circuitry and a head disk assembly (HDA)
14 comprising the disk, an actuator arm, a head connected to a distal end of the actuator arm, and a
15 voice coil motor for rotating the actuator arm about a pivot to position the head radially over the
16 disk. The disk comprises a plurality of spiral tracks, wherein each spiral track comprises a high
17 frequency signal interrupted at a predetermined interval by a sync mark. The head internal to the
18 disk drive is used to read the high frequency signal in the spiral tracks to generate a position error
19 signal used to maintain the head along a substantially circular target path. The sync marks in the
20 spiral tracks are read to generate a spiral sync mark detect signal, and a coarse timing recovery
21 measurement is generated in response to the spiral sync mark detect signal. A fine timing
22 recovery measurement is generated in response to the high frequency signal in the spiral tracks,
23 and a servo write clock is synchronized in response to the coarse timing recovery measurement
24 and the fine timing recovery measurement. The servo write clock and the head internal to the
25 disk drive are used to write the product servo sectors along the circular target path.

26 In one embodiment, the spiral tracks are written to the disk using an external spiral servo
27 writer.

1 In another embodiment, the sync marks in the spiral tracks are detected synchronously
2 from synchronous read signal sample values. In one embodiment, the servo write clock is used
3 to sample a read signal emanating from the head to generate the synchronous read signal sample
4 values.

5 In yet another embodiment, the step of generating the coarse timing recovery
6 measurement comprises the step of comparing an expected value of a modulo N counter to an
7 actual value of the modulo N counter when one of the sync marks is detected.

8 In still another embodiment, the step of generating the fine timing recovery measurement
9 comprises the step of computing a timing gradient in response to expected read signal sample
10 values and actual read signal sample values.

11 In one embodiment, the control circuitry within the disk drive is used to read the spiral
12 tracks in order to synchronize the servo write clock. In an alternative embodiment, an external
13 product servo writer is used to read the spiral tracks in order to synchronize the servo write clock.

14 The present invention may also be regarded as a disk drive comprising a disk having a
15 plurality of spiral tracks, wherein each spiral track comprises a high frequency signal interrupted
16 at a predetermined interval by a sync mark. The disk drive further comprises an actuator arm, a
17 head connected to a distal end of the actuator arm, and a voice coil motor for rotating the actuator
18 arm about a pivot to position the head radially over the disk. The head internal to the disk drive
19 is used to read the high frequency signal in the spiral tracks to generate a position error signal
20 used to maintain the head along a substantially circular target path. The sync marks in the spiral
21 tracks are read to generate a spiral sync mark detect signal, and a coarse timing recovery
22 measurement is generated in response to the spiral sync mark detect signal. A fine timing
23 recovery measurement is generated in response to the high frequency signal in the spiral tracks,
24 and a servo write clock is synchronized in response to the coarse timing recovery measurement
25 and the fine timing recovery measurement. The servo write clock and the head internal to the
26 disk drive are used to write product servo sectors along the circular target path.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a prior art disk format comprising a plurality of radially spaced, concentric tracks defined by a plurality of product servo sectors.

FIG. 2A and 2B illustrate an embodiment of the present invention wherein an external spiral servo writer is used to write a plurality of spiral tracks to the disk for use in writing product servo sectors to the disk.

FIG. 3A shows an embodiment of the present invention wherein a servo write clock is synchronized by clocking a modulo-N counter relative to when the sync marks in the spiral tracks are detected.

FIG. 3B shows an eye pattern generated by reading the spiral track, including the sync marks in the spiral track.

FIG. 4 illustrates an embodiment of the present invention wherein synchronization of the servo write clock is maintained from a coarse timing recovery measurement generated in response to the sync marks recorded in the spiral tracks and a fine timing recovery measurement generated in response to the high frequency signal in the spiral tracks.

FIG. 5 shows circuitry according to an embodiment of the present invention for generating the servo write clock including a sync detector for detecting the sync marks in the spiral tracks and timing recovery for adjusting the frequency of a write voltage controlled oscillator (VCO).

FIG. 6 shows an embodiment of the timing recovery circuitry wherein a phase error is generated from read signal sample values and expected sample values, and the servo write clock is used to synchronously sample the read signal.

FIG. 7 illustrates the read signal sample values, the expected sample values, and the corresponding phase error.

FIG. 8 shows an alternative embodiment wherein the timing recovery circuitry comprises an interpolator and a read VCO is used to sample the read signal.

FIG. 9 shows an embodiment of the present invention wherein an external product servo writer is used to process the spiral tracks in order to write the product servo sectors to the disk.

FIG. 10 shows an embodiment of the present invention wherein an external spiral servo writer is used to write the spiral tracks, and a plurality of external product servo writers write the product servo sectors for the HDAs output by the external spiral servo writer.

FIG. 11 shows an embodiment of the present invention wherein an external spiral servo writer is used to write the spiral tracks, and the control circuitry within each product disk drive is used to write the product servo sectors.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGs. 2A and 2B show a disk drive 16 according to an embodiment of the present invention comprising a disk 18 having a plurality of spiral tracks 20_0 - 20_N , wherein each spiral track 20 comprises a high frequency signal 22 interrupted at a predetermined interval by a sync mark 24 (FIG. 3B). The disk drive 16 further comprises an actuator arm 26, a head 28 connected to a distal end of the actuator arm 26, and a voice coil motor 30 for rotating the actuator arm 26 about a pivot to position the head 28 radially over the disk 18. The head 28 internal to the disk drive 16 is used to read the high frequency signal 22 in the spiral tracks 20 to generate a position error signal used to maintain the head 28 along a substantially circular target path. The sync marks 24 in the spiral tracks 20 are read to generate a spiral sync mark detect signal, and a coarse timing recovery measurement is generated in response to the spiral sync mark detect signal. A fine timing recovery measurement is generated in response to the high frequency signal 22 in the spiral tracks 20, and a servo write clock is synchronized in response to the coarse timing recovery measurement and the fine timing recovery measurement. The servo write clock and the head 28 internal to the disk drive 16 are used to write product servo sectors along the circular target path.

In the embodiment of FIG. 2A, the disk 18, actuator arm 26, head 28 and voice coil motor 30 are enclosed in a head disk assembly (HDA) 32 of the disk drive 16. The disk drive 16 further comprises control circuitry 34 mounted on a printed circuit board for controlling operation of the disk drive 16. In one embodiment, the control circuitry 34 writes the spiral tracks 20_0 - 20_N to the

1 disk 18 and then processes the spiral tracks 20_0 - 20_N to write the product servo sectors to the disk
2 18.

3 In an alternative embodiment shown in FIG. 2A, an external servo writer 36 is used to
4 write the spiral tracks 20_0 - 20_N to the disk 16. The external spiral servo writer 36 comprises a
5 head positioner 38 for actuating a head positioning pin 40 using sensitive positioning circuitry,
6 such as a laser interferometer. Pattern circuitry 42 generates the data sequence written to the disk
7 18 for the spiral tracks 20_0 - 20_N . The external spiral servo writer 34 writes a clock track 44 (FIG.
8 2B) at an outer diameter of the disk 18, and a clock head 46 is inserted into the HDA 32 for
9 reading the clock track 44 to generate a clock signal 48. Timing circuitry 50 in the external spiral
10 servo writer 36 processes the clock signal 48 to enable the pattern circuitry 42 at the appropriate
11 time so that the spiral tracks 20_0 - 20_N are written at the appropriate circumferential location. The
12 clock signal 48 also enables the pattern circuitry 42 to write the sync marks 24 (FIG. 3B) within
13 the spiral tracks 20_0 - 20_N at the same circumferential location from the outer diameter to the inner
14 diameter of the disk 18. As described below with reference to FIG. 4, the constant interval
15 between sync marks 24 (independent of the radial location of the head 28) enables the servo write
16 clock to maintain synchronization.

17 In the embodiment of FIG. 2A, the entire disk drive 16 is shown as being inserted into the
18 external spiral servo writer 36. In an alternative embodiment, only the HDA 32 is inserted into
19 the external spiral servo writer 36.

20 After the external spiral servo writer 36 writes the spiral tracks 20_0 - 20_N to the disk 18, the
21 head positioning pin 40 and clock head 46 are removed from the HDA 32 and the product servo
22 sectors are written to the disk 18. In one embodiment, the control circuitry 34 within the disk
23 drive 16 is used to process the spiral tracks 20_0 - 20_N in order to write the product servo sectors to
24 the disk 18. In an alternative embodiment described below with reference to FIGs. 9 and 10, an
25 external product servo writer is used to process the spiral tracks 20_0 - 20_N in order to write the
26 product servo sectors to the disk 18 during a "fill operation".

FIG. 3B illustrates an “eye” pattern in the read signal that is generated when the head 28 passes over a spiral track 20. The read signal representing the spiral track comprises high frequency transitions 22 interrupted by sync marks 24. When the head 28 moves in the radial direction, the eye pattern will shift (left or right) while the sync marks 24 remain fixed. The shift in the eye pattern (detected from the high frequency signal 22) relative to the sync marks 24 provides the off-track information for servoing the head 28.

FIG. 3A shows an embodiment of the present invention wherein a saw-tooth waveform 52 is generated by clocking a modulo-N counter with the servo write clock, wherein the frequency of the servo write clock is adjusted until the sync marks 24 in the spiral tracks 20_0 - 20_N are detected at a target modulo-N count value. The servo write clock may be generated using any suitable circuitry. In one embodiment, the servo write clock is generated using a phase locked loop (PLL). As each sync mark 24 in the spiral tracks 20_0 - 20_N is detected, the value of the modulo-N counter represents the phase error for adjusting the PLL. In one embodiment, the PLL is updated when any one of the sync marks 24 within the eye pattern is detected. In this manner the multiple sync marks 24 in each eye pattern (each spiral track crossing) provides redundancy so that the PLL is still updated if one or more of the sync marks 24 are missed due to noise in the read signal. Once the sync marks 24 are detected at the target modulo-N count values, the servo write clock is coarsely locked to the desired frequency for writing the product servo sectors to the disk 18.

The sync marks 24 in the spiral tracks 20_0 - 20_N may comprise any suitable pattern, and in one embodiment, a pattern that is substantially shorter than the sync mark 10 in the conventional product servo sectors 2 of FIG. 1. A shorter sync mark 24 allows the spiral tracks 20_0 - 20_N to be written to the disk 18 using a steeper slope (by moving the head faster from the outer diameter to the inner diameter of the disk 18) which reduces the time required to write each spiral track 20_0 - 20_N .

In one embodiment, the servo write clock is further synchronized by generating a timing recovery measurement from the high frequency signal 22 between the sync marks 24 in the spiral

1 tracks 20₀-20_N. Synchronizing the servo write clock to the high frequency signal 22 helps
2 maintain proper radial alignment (phase coherency) of the Gray coded track addresses in the
3 product servo sectors. The timing recovery measurement may be generated in any suitable
4 manner. In one embodiment, the servo write clock is used to sample the high frequency signal
5 22 and the signal sample values are processed to generate the timing recovery measurement. The
6 timing recovery measurement adjusts the phase of the servo write clock (PLL) so that the high
7 frequency signal 22 is sampled synchronously. In this manner, the sync marks 24 provide a
8 coarse timing recovery measurement and the high frequency signal 22 provides a fine timing
9 recovery measurement for maintaining synchronization of the servo write clock.

10 FIG. 4 illustrates how the product servo sectors 56₀-56_N are written to the disk 18 after
11 synchronizing the servo write clock in response to the high frequency signal 22 and the sync
12 marks 24 in the spiral tracks 20₀-20_N. In the embodiment of FIG. 4, the dashed lines represent
13 the centerlines of the data tracks. The sync marks in the spiral tracks 20₀-20_N are written so that
14 there is a shift of two sync marks in the eye pattern (FIG. 3B) between data tracks. In an
15 alternative embodiment, the sync marks in the spiral tracks 20₀-20_N are written so that there is a
16 shift of N sync marks in the eye pattern between data tracks. In practice the width of the spiral
17 tracks 20₀-20_N in the embodiment of FIG. 4 will be proximate the width of a data track. The
18 spiral tracks 20₀-20_N are shown in FIG. 4 as being wider than the width of a data track for
19 illustration purposes.

20 The PES for maintaining the head 28 along a servo track (tracking) may be generated
21 from the spiral tracks 20₀-20_N in any suitable manner. In one embodiment, the PES is generated
22 by detecting the eye pattern in FIG. 3B using an envelope detector and detecting a shift in the
23 envelope relative to the sync marks 24. In one embodiment, the envelope is detected by
24 integrating the high frequency signal 22 and detecting a shift in the resulting ramp signal. In an
25 alternative embodiment, the high frequency signal 22 between the sync marks 24 in the spiral
26 tracks are demodulated as servo bursts and the PES generated by comparing the servo bursts in a
27 similar manner as the servo bursts 14 in the conventional servo sectors (FIG. 1).

Once the head 28 is tracking on a servo track, the product servo sectors 56_0 - 56_N are written to the disk using the servo write clock. Write circuitry is enabled when the modulo-N counter reaches a predetermined value, wherein the servo write clock clocks the write circuitry to write the product servo sector 56 to the disk. The spiral tracks 20_0 - 20_N on the disk are processed in an interleaved manner to account for the product servo sectors 56_0 - 56_N overwriting a spiral track. For example, when writing the product servo sectors 56_1 to the disk, spiral track 20_2 is processed initially to generate the PES tracking error and the timing recovery measurement. When the product servo sectors 56_1 begin to overwrite spiral track 20_2 , spiral track 20_3 is processed to generate the PES tracking error and the timing recovery measurement.

FIG. 5 shows details of control circuitry for synchronizing the servo write clock 58. The read signal 60 emanating from the head 28 is sampled 62, and the read signal sample values 64 are processed by a sync mark detector 66 for detecting the sync marks 24 in the spiral tracks 20_0 - 20_N . The sync mark detector 66 generates a sync mark detect signal 68 applied to a timing recovery circuit 70. The timing recovery circuit 70 processes the sync mark detect signal 68 to generate a coarse timing recovery measurement, and the read signal sample values 64 representing the high frequency signal 22 in the spiral tracks 20_0 - 20_N to generate a fine timing recovery measurement. The coarse and fine timing recovery measurements are combined to generate a control signal applied to a write voltage controlled oscillator (VCO) 72 which outputs the servo write clock 58. The servo write clock 58 clocks operation of write circuitry 74 for writing the product servo sectors 56_0 - 56_N to the disk 18. The servo write clock 58 is also fed back into the timing recovery circuit 70 and used to generate the coarse timing recovery measurement. The timing recovery circuit 70 generates a sync mark detection window over line 78 for enabling the sync mark detector 66 during a window where a sync mark 24 is expected to occur. The timing recovery circuit 70 also generates a control signal over line 80 to enable the write circuitry 74 to begin writing a product servo sector at the appropriate time.

FIG. 6 shows details of a suitable timing recovery circuit 70 according to an embodiment of the present invention wherein the servo write clock 58 is used to synchronously sample 62 the

1 read signal 60 to generate synchronous read signal sample values 64. A phase error detector 82
2 detects a phase error ϕ 84 between the read signal sample values 64 (arrows in FIG. 7) and
3 expected sample values 88 (circles in FIG. 7). An expected sample generator 86 generates the
4 expected sample values 88 input into the phase error detector 82. The phase error detector 82
5 generates the phase error ϕ 84 by implementing a suitable stochastic gradient equation. In one
6 embodiment, the expected sample generator 86 processes the read signal samples 64 to initialize
7 a state machine which then outputs the expected sample values 88. Referring to FIG. 7, after
8 being initialized the state machine generates the sequence $(\dots +A, +A, -A, -A, +A, +A, -A, -A, \dots)$. In
9 one embodiment, a high bandwidth gain loop maintains the gain of the read signal sample values
10 64 at a target level to compensate for the amplitude variation in the read signal 60 (the eye
11 pattern of FIG. 3B) as the head 28 passes over a spiral track 20. In an alternative embodiment,
12 the amplitude A of the expected sample values 88 is adjusted relative to the amplitude of the read
13 signal 60. For example, an envelope detector can track the amplitude of the eye pattern (FIG.
14 3B) and then adjust the amplitude A of the expected sample values 88 accordingly.

15 The servo write clock 58 also clocks a modulo N counter 90. When the sync mark
16 detector 66 detects a sync mark 24 in a spiral track 20, the content of the modulo N counter 90 is
17 subtracted 92 from an expected count value 94 to generate the coarse timing recovery
18 measurement 96. The coarse timing recovery measurement 96 and the fine timing recovery
19 measurement (phase error ϕ 84) are combined 98 and filtered by a loop filter 100. The output of
20 the loop filter 100 is a frequency control signal 102 applied to the write VCO 72 in order to
21 synchronize the servo write clock 58.

22 Any suitable technique may be used to generate the fine timing recovery measurement
23 (phase error ϕ) from the high frequency signal 22 in the spiral tracks 20. In one embodiment, a
24 suitable trigonometric identity is employed to generate the phase error ϕ in a manner that is
25 substantially independent of the amplitude variations in the read signal 60.

26 FIG. 8 shows details of a timing recovery circuit 70 according to an alternative
27 embodiment of the present invention employing interpolated timing recovery (ITR). A read

VCO 101 samples 62 the reads signal 60 at a constant frequency to generate asynchronous sample values 64. A phase error detector 82 generates a phase error ϕ 84 between the expected sample values 88 and the asynchronous sample values 64. An interpolator 102 interpolates the asynchronous sample values 64 using the phase error ϕ 84 to generate synchronous sample values 103 processed by the sync mark detector 66 and the expected sample value generator 86. The interpolator 102 may employ any suitable circuitry, and in one embodiment implements a finite impulse response filter with variable coefficients for performing the interpolation. The remaining components in the timing recovery circuit 70 of FIG. 8 operate as described above with reference to FIG. 6 to generate a frequency control signal 102 applied to the write VCO 72 in order to synchronize the servo write clock 58. In one embodiment the read VCO 101 and the write VCO 72 are implemented on the same substrate so that they exhibit substantially the same center frequency and temperature drift.

FIG. 9 shows an embodiment of the present invention wherein after writing the spiral tracks 20_0 - 20_N to the disk 18 (FIG. 2A-2B), the HDA 32 is inserted into an external product servo writer 104 comprising suitable circuitry for reading and processing the spiral tracks 20_0 - 20_N in order to write the product servo sectors 56_0 - 56_N to the disk 18. The external product servo writer 104 comprises a read/write channel 106 for interfacing with a preamp 108 in the HDA 32. The preamp 108 amplifies a read signal emanating from the head 28 over line 110 to generate an amplified read signal applied to the read/write channel 106 over line 112. The read/write channel 106 comprises circuitry for generating servo burst signals 113 applied to a servo controller 114. The servo controller 114 processes the servo burst signals 113 to generate the PES. The PES is processed to generate a VCM control signal applied to the VCM 30 over line 116 in order to maintain the head 28 along a circular path while writing the product servo sectors 56_0 - 56_N . The servo controller 114 also generates a spindle motor control signal applied to a spindle motor 118 over line 120 to maintain the disk 18 at a desired angular velocity. Control circuitry 122 processes information received from the read/write channel 106 over line 124 associated with the spiral tracks 20_0 - 20_N (e.g., timing information) and provides the product servo sector data to the

1 read/write channel 106 at the appropriate time. The product servo sector data is provided to the
2 preamp 108 which modulates a current in the head 28 in order to write the product servo sectors
3 56_0 - 56_N to the disk 18. The control circuitry 122 also transmits control information over line 126
4 to the servo controller 114 such as the target servo track to be written. After writing the product
5 servo sectors 56_0 - 56_N to the disk 18, the HDA 32 is removed from the external product servo
6 writer 104 and a printed circuit board assembly (PCBA) comprising the control circuitry 34 (FIG.
7 2A) is mounted to the HDA 32.

8 In one embodiment, the external product servo writer 104 of FIG. 9 interfaces with the
9 HDA 32 over the same connections as the control circuitry 34 to minimize the modifications
10 needed to facilitate the external product servo writer 104. The external product servo writer 104
11 is less expensive than a conventional servo writer because it does not require a clean room or
12 sophisticated head positioning mechanics. In an embodiment shown in FIG. 10, a plurality of
13 external product servo writers 104_0 - 104_N process the HDAs 32_{i-i+N} output by an external spiral
14 servo writer 36 in order to write the product servo sectors less expensively and more efficiently
15 than a conventional servo writer. In an alternative embodiment shown in FIG. 11, an external
16 spiral servo writer 36 is used to write the spiral tracks, and the control circuitry 34 within each
17 product disk drive 16_0 - 16_N is used to write the product servo sectors.